

APPLICATION FOR U.S. LETTERS PATENT

TITLE:
**ENHANCED CONDUCTIVITY BODY BIASED
PMOS DRIVER**

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Ex.Mail No. EL372085131US
Docket N . 2207/5975

ENHANCED CONDUCTIVITY BODY BIASED PMOS DRIVER

Field Of The Invention

The present invention pertains to the field of semiconductor circuits. More particularly,
5 the present invention pertains to semiconductor circuits having a transistor whose body is biased.

Background Of The Invention

A conventional complementary metal oxide semiconductor (CMOS) transistor typically
has to be able to provide a certain level of drive current in order to reliably communicate with or
10 control or drive another device. The drive current is a function of the threshold voltage of the
transistor and the voltage levels applied to the terminals of the transistor, among other factors.
The threshold voltage, V_t , may be defined as the voltage applied between the gate and source
below which the drive or drain-to-source current, I_{ds} , drops to very close to zero.

Transistors which are designed to be used with relatively high voltage levels (high
15 voltage level transistors) and which have a relatively high threshold voltage may produce
relatively high drive currents if they are used in circuits supplying relatively high voltage levels.
Problems, however, arise when attempting to use a high voltage level transistor in a low voltage
level circuit. For example, if a transistor which is designed for use with 3.3 volts at its terminals
is used in a circuit supplying 1.5 volts the drive current produced by the transistor is likely to be
20 rather low in comparison to the same transistor used in a circuit providing 3.3 volts. An
input/output (I/O) buffer is an example of a situation where multiple voltages may need to be
supported by a transistor. Part of the low performance is due to the large threshold voltage
inherent in a transistor designed for use with 3.3 volts. Typically, if a transistor is to be used
with a large voltage applied to the source, source voltage, the gate oxide is made relatively thick
25 in order to prevent oxide breakdown of the gate oxide which may render the transistor

inoperable. Unfortunately, the threshold voltage increases as the thickness of the gate oxide of a transistor increases, causing the drive current to decrease. Consequently, when a transistor having a large threshold voltage is used with terminal voltages that are lower than the voltages it was designed to be used with, the drive current is typically relatively low.

5 However, the drive current can be increased by changing the threshold voltage. With a lower threshold voltage, a transistor can provide a greater drain current for a given voltage applied between the gate and source, V_{gs} . Circuit schemes have been proposed where a forward bias is applied statically or dynamically to the body node of a metal oxide semiconductor field effect transistor (MOSFET) to decrease the threshold voltage and increase the drive current when
10 the MOSFET is turned on.

 An example of a circuit scheme which allows transistors to have both a higher drive current when turned on and a lower leakage current when turned off is illustrated in **Figures 1a** and **1b**. **Figures 1a** and **1b** illustrate a circuit 100 which includes transistor 110 having a source
15 111 at a source voltage V_{CC} , a drain 113, and a gate 112. Gate 112 is coupled to coupling capacitor 114 which in turn is coupled to the body 115 of transistor 110. Circuit 100 includes explicitly placed diode 117 which couples source 111 to tap 116. Transistor 110 includes parasitic diodes 115a and 115b.

 Transistor 110 is a p-channel metal oxide semiconductor (PMOS) transistor in which a body or substrate is a doped n type material, and source 111 and drain 113 are each of p+ type
20 material. An n or n+ type material refers to material to which donor dopant has been added to increase the electron concentration. An n+ material has an even greater electron concentration than n type material. A p or p+ type material refers to material to which acceptor dopant has been added to increase the hole concentration. A p+ material has an even greater hole concentration than p type material. A n+ type tap provides a path from coupling capacitor 114 to
25 body 115. When the gate voltage is low, a channel 118 provides a path between source 111 and

drain 113. Transistor 110 has a threshold voltage V_t that may be defined as the voltage applied between the gate and source below which the drive or drain-to-source current, I_{ds} , drops to very close to zero.

5 A body bias is applied to body 115 through tap 116. When transistor 110 is in an active mode, the body bias is such that a forward bias is applied to body 115. The threshold voltage without forward body bias is $V_t(NFB)$. The threshold voltage with a forward bias is $V_t(WFB)$. In practice, $|V_t(WFB)|$ is lower than $|V_t(NFB)|$. With a lower threshold voltage, transistor 110 can provide a greater drive current for a given V_{gs} . For example, transistor 110 in a forward body bias condition can provide the same drive current with a lower V_{gs} as compared to
10 transistor 110 not in a forward bias condition. Likewise, transistor 110 in a forward bias condition can provide a greater drive current with the same V_{gs} and V_{cc} as compared to transistor 110 not in a forward bias condition.

Since a forward bias has a tendency to increase leakage current of transistor 110, which is undesirable, it is desirable to reverse bias body 115 when transistor 110 is off. In circuit 100, body
15 115 is reverse biased when transistor 110 is in an inactive mode and the body is at V_{cc} or a higher potential.

Unfortunately, circuit 100, since it was designed for use in the core of an integrated circuit, does not provide good electrostatic discharge (ESD) protection, has a capacitor 114 which takes up a relatively large area, and undergoes modulation of the threshold voltage due to noise.

20 During an ESD, kilovolts of voltage may be placed across a device for nanoseconds.

One way to address this issue is to place an explicit large ESD diode 139 in parallel with transistor 130 as illustrated in **Figure 1c**. **Figure 1c** illustrates a circuit for biasing the body of a transistor having electrostatic discharge protection. Diode 139 is forward biased when drain 133 is at a higher voltage with respect to source supply voltage, V_{cc} . However due to high currents and resistance of diode 139, voltages upwards of 1V may exist between drain 133 and the V_{cc}
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even when the ESD diode is clamping. Therefore, diode 135b and diode 137 are forward biased and conduct. Since diode 137 is small, it cannot handle large currents, and can be easily destroyed. Consequently, diode 137 either needs to be sized up significantly, or another mechanism for dealing with ESD's needs to be provided. Increasing the size of diode 137 may be undesirable in applications where die area is limited.

Similarly, coupling capacitor 114 takes up a relatively large die area which may be undesirable in applications where area is limited.

Circuit 100 does not provide for the communication of the body bias produced by coupling capacitor 114 to bodies other than the body of the transistor to which capacitor 114 is coupled. In a typical I/O circuit which has actual drivers that communicate with an external bus, the impedance of the drivers is dynamically adjusted or compensated by using a calibration cell which contains a calibration driver whose impedance is matched to a reference impedance. The adjustments or compensation made to the calibration driver impedance are also made to the actual drivers. For the compensation to be properly made, a common bias needs to be used for both the actual drivers and the calibration driver or drivers. Since capacitor 114 does not provide for relatively easy and repeatable communication of substantially the same bias to multiple transistors, compensation may not be properly done.

Additionally, circuit 100 does not have a very good conduction path when it is operating between regions where diode 117 is conducting (gate 112 going from low to high) or when diode 115a is conducting (gate 112 going from high to low). This leaves a window between ($V_{cc} + \text{voltage drop across diode 117}$) and ($V_{cc} - \text{voltage drop across diode 115a}$) when the N-well is relatively floating. Any I/O noise caused by reflections, bus switching, or other noise sources is coupled into the N-well and cannot be dissipated. This noise modulates the threshold voltage. The diodes 117 and 115a and capacitor 114 also form a peak detect circuit. For example if diode 115a is conducting, then the highest voltage achieved by the V_{cc} will bias the

N-well to ($V_{ccmax} - V_{diode}$) level. When the source supply voltage, V_{cc} , collapses, the N-well cannot track as there is no conduction path.

Since ESD impulse may destroy a transistor, it is desirable to provide a relatively larger drive current when the transistor is turned on using a circuit scheme that will provide relatively better protection from ESD impulses without the area cost of an added ESD diode. Furthermore, since a coupling capacitor takes up a relatively large die area, it is desirable to provide a relatively larger drive current when the transistor is turned on using a circuit scheme that does not require a capacitor. Finally, it is desirable to provide a relatively larger driver current when the transistor is turned on using a circuit scheme that does not cause threshold voltage modulation.

Summary of the Invention

According to one embodiment of the present invention a method for biasing a body of a transistor is described. The method includes detecting a voltage applied to a terminal of a transistor and coupling a biasing voltage to the body based upon the detected voltage.

Brief Description of the Drawings

The present invention is illustrated by way of example, and not limitation, in the figures of the accompanying drawings in which:

Figures 1a and 1b illustrate a circuit for biasing the body of a transistor;

Figure 1c illustrates a circuit for biasing the body of a transistor having electrostatic discharge protection; and

Figures 2a and 2b illustrate a circuit for biasing the body of a transistor according to one embodiment of the present invention;

Figure 3a illustrates a circuit for biasing the body of a transistor according to another embodiment of the present invention;

Figure 3b illustrate a current source for biasing the body of a transistor according to one embodiment of the present invention; and

5 **Figure 4** illustrates a circuit for controlling a bias voltage applied to the body of a transistor according to one embodiment of the present invention.

Detailed Description

10 A method and apparatus for controlling the drain current of a transistor. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be evident, however, to one skilled in the art that the present invention may be practiced in many types of circuits, especially integrated circuits having a driver for a digital bus, without these specific details. In other instances well known operations, functions and devices are not shown in order to avoid
15 obscuring the invention. Repeated usage of the phrases "in one embodiment," "in an embodiment," "an alternative embodiment," or "an alternate embodiment" does not necessarily refer to the same embodiment, although it may.

20 **Figures 2a and 2b** illustrate a circuit for controlling the drain current of a transistor for one embodiment in accordance with the present invention. Circuit 200 includes transistor 210 having a source 211 at a source voltage V_{cc} , a drain 213, and a gate 212 receiving a gate voltage V_g . Gate 212 is coupled to inverter 221 which is coupled to inverter 222 which in turn is coupled to a body 215 of transistor 110. For alternative embodiments in accordance with the present invention, there may be resistors, transistors or other elements between V_{cc} , V_g , and drain 213, source 211, and gate 212.

Transistor 210 is a p-channel metal oxide semiconductor (PMOS) transistor in which body 215 or substrate 215 is a doped n type material, and source 211 and drain 213 are each of p+ type material. n or n+ type material refers to material to which donor dopant has been added to increase the electron concentration. n+ material has an even greater electron concentration than n type material. p or p+ type material refers to material to which acceptor dopant has been added to increase the hole concentration. p+ material has an even greater hole concentration than p type material. An n+ type tap (not shown) provides a path from inverter 222 to body 215. Transistor 210 includes parasitic diodes 215a and 215b. When V_g is low, a channel 218 provides a path between source 211 and drain 213. Transistor 210 has a threshold voltage, V_t , that may be defined as the voltage applied between the gate and source below which the drive or drain-to-source current, I_{ds} , drops to very close to zero.

The threshold voltage, V_t , changes depending upon the voltage applied to the tap (not shown). When the gate is driven low, a low voltage is applied to the tap causing body 215 to be forward biased, leading to a lower V_t and an increase in drive current and faster switching for a given V_{gs} , V_{cc} , and V_{ds} . V_{gs} is the gate to source voltage, and V_{ds} is the drain to source voltage. When transistor 210 is in active mode, the voltage at tap 216 will be at (V_{cc} – voltage drop across parasitic diode 215a). On the other hand, when the gate is driven high, body 215 is driven to the same potential as V_{cc} leading to a nominal V_t .

Circuit 200 allows the drive current to be increased by forward biasing the body and without having to increase the size of transistor 210 or use a coupling capacitor. Increasing the drive current without increasing the size of the transistors or using coupling capacitors is desirable, since the size of transistors and the size of circuits that allow forward and reverse biasing is restricted in some applications.

In addition to lowering the V_t of transistor 210 without using a coupling capacitor between gate 212 and body 215, circuit 200 provides good electrostatic discharge (ESD)

protection. An ESD impulse received at drain 213 will travel through parasitic diode 215b and body 215, emerge from tap 216 and travel through body of inverter 222 to ground, rather than hit the diode 117 and possibly destroy it. Providing good ESD protection may be essential for maintaining the integrity of circuits at the periphery of an integrated circuit that couple the integrated circuit to other external circuits.

An important feature is to share a common bias voltage among multiple I/O transistors. Some of these transistors can be employed in impedance compensation circuits and others employed for real I/O drivers and circuits. Therefore both the compensation and real I/O transistors operate at the same bias level.

Figure 3a illustrates a circuit for controlling the drain current of a transistor for one embodiment in accordance with the present invention. Circuit 300 includes current source 320, and transistor 310 which includes a source 311 at a source voltage V_{cc} received from a source voltage supply, a drain 313, and a gate 312 receiving a gate voltage V_g . Transistor 310 includes body 315 and tap (not shown) coupled to current source 320. Circuit 300 operates in a manner similar to circuit 200 and need not be described in great detail here. Transistor 310 includes parasitic diodes 315a and 315b. Current source 320 forces the current through diode 315a, thereby biasing body 315 with a bias voltage greater than (V_{cc} – the voltage drop across parasitic diode 315a), when the gate is driven by a low voltage. By forward biasing body 315, the threshold voltage of transistor 310 can be lowered improving the drain current. Current source 320 biases body 315 to V_{cc} when the gate is driven by a high voltage.

While in the description above current source 320 provides a bias to transistor 310, for alternative embodiments in accordance with this invention current source 320 provides a bias to multiple transistors. Being able to provide a common bias to multiple transistors is especially useful in I/O circuits. In a typical I/O circuit which has actual drivers that communicate with an external bus, the impedance of the drivers is dynamically adjusted or compensated by using a

calibration cell which contains a calibration driver whose impedance is matched to a reference impedance. The adjustments or compensation made to the calibration driver impedance are also made to the actual drivers. For the compensation to be properly made, a common bias needs to be used for both the actual drivers and the calibration driver or drivers. For alternative
5 embodiments, current source 320 provides a common bias to multiple transistors allowing compensation to be done in a more accurate manner.

In addition to lowering the threshold voltage of transistor 310 without using a coupling capacitor between gate 312 and body 315, circuit 300 provides good electrostatic discharge (ESD) protection since an ESD impulse at the drain is not directly coupled to a small diode.

10 Figure 3b illustrates a current source for one embodiment in accordance with the present invention. Current source 320 includes n-channel metal oxide semiconductor (NMOS) transistor 324, NMOS transistor 325, bypass capacitor 326, switches 321, 322 and 323, and diode 327.

When gate 312 of transistor 310 is driven low, switches 321 and 322 are opened, and switch 323 is closed causing diode 327 to conduct causing the voltage at gate 325g of transistor 325 to be
15 V_{cc} - the voltage across diode 327. The voltage across diode 327 is referred to as V_{diode} .

V_{diode} is a function of the doping levels and other design characteristics of diode d2. Transistors 324 and 325 form a current mirror. Transistor 324 will turn on because of $(V_{cc} - V_{diode})$ at gate 325g. The degree to which transistor 324 turns on depends on how strongly transistor 325 turns on. The ratio of widths of transistors 324 to 325 sets the biasing current ratio in the
20 combined diodes (315a) and diode 327. Since transistor 324 conducts, parasitic diode 315a conducts causing a bias voltage (V_{cc} - voltage across parasitic diode 315a) to appear at body 315 of transistor 310. A capacitor 326 may be placed in the bias node to decouple any AC noise.

When the tristate signal is driven high, switch 323 is opened, and switches 321 and 323 are closed causing transistors 324 and 325 to turn off, the bias voltage applied to the body of

transistor 310 is raised to V_{cc} . Consequently, the leakage current of transistor 310 when transistor 310 is in inactive mode is kept relatively low.

It should be appreciated that circuit 320 is one of many ways for providing a current source known in the art. Consequently, this invention should not be limited to current source 320 described above.

Figure 4 illustrates a circuit for controlling the drain current of a transistor for another embodiment in accordance with the present invention. Circuit 400 is similar to circuit 200 and need not be described in great detail here. Circuit 400 includes a NOR gate 421, and a source voltage detector 440 coupled to a source voltage supply providing a source voltage, V_{cc} . Source voltage detector 440 detects the source voltage and applies a low voltage to NOR gate 421 if the source voltage is lower than a predetermined high source voltage. Otherwise voltage detector 440 applies V_{cc} . When NOR gate 421 receives a low voltage and gate 412 is driven low, the output of gate 421 is high and the output of inverter 422 is low, causing body 415 to be forward biased. The high source voltage used in an application is an implementation detail, and the present invention is not limited to any particular high source voltage. For example, for one embodiment, the gate voltage is coupled to inverter 421 if the source voltage is less than 3.3 volts.

Circuit 400 allows transistors whose gate oxide is thick, causing the transistor to have a relatively large threshold voltage, to have a larger drain current than would otherwise be possible. Typically, a transistor is designed with a large gate oxide thickness in order to protect the transistor from punch through of the gate when used with large source voltages.

Unfortunately, large gate oxide thickness results in a large threshold voltage. A large threshold voltage may have a detrimental effect on the drain current when a relatively small source voltage is applied to the transistor. This detrimental effect can be demonstrated by first noting that the relationship between threshold voltage, V_t , and drain current (I_{ds}) can be expressed by $k \cdot (V_{gs} -$

V_t). When the source voltage decreases V_{gs} decreases but the threshold voltage remains substantially the same. It is desirable to decrease the threshold voltage when V_{gs} is decreased. By biasing the body, the threshold voltage can be decreased, increasing the drain current even though the source voltage has decreased. Consequently, transistors, which would otherwise have to be made larger in order to increase the drain current, can be used in their original size and with a lower source supply voltage. Thus, circuit 400 provides the ability to use two (or more) different source supply voltages with the same transistor by allowing the transistor's threshold voltage to be dynamically decreased, improving the transistor's drain current at the lower supply voltage.

While in the above description detector 440 is placed in parallel with NOR gate 412. While in the above description detector 420 is used with circuit 200 of Figure 2, it should be appreciated that for an alternative embodiment in accordance with the present invention detector 440 can be used with circuit 300 of Figure 3a. In such an alternative embodiment, detector 440 couples the output of the direct current source 320 to the tap (not shown) of transistor 310 when the source supply voltage is below the high source voltage.

While in the above description a voltage detector 440 is used to dynamically adjust the threshold voltage, it should be appreciated that in alternative embodiments a switch(es) or jumper(s) can be set by a user to select from two or more voltages each of which causes a current source such as source 320 to generate an associated bias for application to the body of a transistor.

While transistors 210, 310, and 410 are PMOS transistors according to some embodiments of the present invention, it should be appreciated that in alternative embodiments in accordance with the present invention transistors 210, 310, and 410 can be NMOS transistors if the body is accessible.

Thus, a method and apparatus for generating reference voltages has been described.

Although the present invention has been described with reference to specific exemplary
embodiments, it will be appreciated by one of ordinary skill in the art that various modifications
and changes may be made to these embodiments without departing from the broader spirit and
5 scope of the invention as set forth in the claims. Accordingly, the specification and drawings are
to be regarded in an illustrative rather than a restrictive sense.